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A review of clean energy innovation and technology transfer in China

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ABSTRACT

China's emergence as a major force in clean energy development has profound implications for the world. A lack of understanding around the trajectory of China's surge in clean energy investment, and the seriousness of its impact on global clean energy development, demands a clear review of China's clean energy innovation. To this purpose, the paper analyzes the technology innovation process and major players for technology innovation in a general sense. It then decodes the Chinese way of innovation, which reflects unique historical circumstances and development stage. The paper also explores the clean energy innovation with Chinese characteristics as well as analyzes lessons from China in clean energy innovation. The paper concludes that China has become a global learning laboratory of clean energy technology. China's leadership in commercializing clean energy technology could ultimately help lower its costs and promote its commercialization globally. Nevertheless, China's clean energy innovation faces an ambiguous future due to the challenge in balancing and coordinating technology import and indigenous innovation.

Contents

1. Introduction . . . 487
2. Understanding technology innovation . . . 487
 2.1. The innovation process . . . 487
 2.2. A valley of death in the innovation process . . . 488
 2.3. Major players and the role of government . . . 488
 2.4. Challenges for innovation . . . 488
3. The Chinese way of innovation . . . 489
 3.1. Innovation as a national strategy . . . 489
 3.2. Science, technology, and innovation governance . . . 489
 3.3. China's quest for indigenous innovation . . . 490
  3.3.1. Legislation, policy and institutional arrangements . . . 491
  3.3.2. The strategy of "market for technology" . . . 491
  3.3.3. R&D, talent, and award programs . . . 491
  3.3.4. Major national science and technology innovation performers . . . 492
4. Clean energy technology innovation with Chinese characteristics . . . 493
 4.1. A strong legacy of a centrally planned economy . . . 493
 4.2. Indigenous innovation through re-innovation . . . 493
 4.3. The role of a global learning laboratory . . . 494
5. Lessons from China . . . 495
 5.1. A broader understanding of technology transfer . . . 495
 5.2. A vicious circle among indigenous innovation, technology transfer, and regulation . . . 496
 5.3. A balanced approach: indigenous innovation vs. technology transfer . . . 496
 5.4. A sober understanding of the role of government in technology innovation . . . 496
 5.5. A reflection of the "state advances as the private sector retreats" . . . 496
6. Conclusions . . . 496
Acknowledgements . . . 497
References . . . 497

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1. Introduction

Climate change, energy security, and economic stability are inextricably linked [1,2]. The ambitious goals that have been set to meet any one of the challenges can never be fully realized without acknowledging and confronting this fact. Over the coming century, the world faces a daunting challenge in powering the world economic growth with a sustained and affordable energy supply without entraining intolerable disruption of global climate by the emissions from fossil-fuel use [3]. There are three main dimensions to the challenge [4–9]:

- **Global energy will remain dominated by fossil fuels in the coming decades, with a majority of the energy-demand growth in developing countries.** According to the International Energy Agency (IEA)'s New Policies Scenario, which assumes that recent government commitments are implemented in a cautious manner, global primary energy demand will increase by one-third between 2010 and 2035, with 90% of the growth in non-Organization for Economic Co-operation and Development (OECD) countries. The share of fossil fuels in global primary energy consumption falls from around 81% today to 75% in 2035. Renewables increase from 13% of the mix today to 18% in 2035.
- **Current practices will not bring clean energy technologies to international markets fast enough.** The speed and scale of the expanding fossil-fuel use have brought a new urgency to deploy the full range of clean energy technologies, from those that reduce conventional pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), to more advanced technologies with higher efficiency and the potential to substantially reduce carbon dioxide (CO_2) emissions. The solutions to the twin challenges of climate change and energy security will therefore largely rely on clean energy innovation. However, global clean energy innovation takes too long under business-as-usual practices. Analysis shows that there is a mismatch between the urgency of addressing climate challenge and the time taken historically for technology systems to evolve and provide a return on investment. Additionally, the current clean energy innovations are unevenly dominated by the OECD countries, which thus will determine the speed and width of diffusion of the most advanced clean energy in the next decades.
- **Energy poverty in developing countries remains a global challenge for the future**. Even with rapidly growing economies in some developing countries, the statistics are still shocking. Today, over 20% of the global population (1.4 billion) lack access to electricity and some 40% of the global population (2.7 billion) rely on the traditional use of biomass for cooking. It's projected that the problem will persist and even deepen in the longer term: 1.2 billion people still lack access to electricity in 2030, and the number of people relying on the traditional use of biomass for cooking rises to 2.8 billion in 2030. The widespread use of biomass leads to deforestation and the serious climate impact of black carbon, which is a major player in global warming. Much worse, the household air pollution from the use of biomass in inefficient stoves would lead to over 1.5 million premature deaths per year in 2030—worse even than premature deaths from malaria, tuberculosis, or HIV/AIDS.

It's an alarming fact that, without accelerating change in global clean energy innovation, the world (particularly developing countries) will lock itself into an insecure, inefficient, and carbon-intensive energy system. To meet the challenge, the capacity of countries to apply sound tools in developing effective national clean energy innovation strategies and programs is thus becoming increasingly important. However, there is a lack of understanding as to the best tools and approaches to planning, designing, and implementing a successful national clean energy strategy [10]. In particular, developing countries usually lack even the basic technological capability or knowledge basis. For these countries, lessons learned and best practices on application of policies and programs in countries similar to their own can be a distinct and uniquely valuable reference guide. China, with nearly $50 billion investment in 2010, is by far the largest source of, and destination for, clean energy investment globally [11]. During the eleventh five-year plan (FYP), covering 2006 through 2010, China invested renminbi (RMB) 5–10 billion (about $700 million–$1.4 billion) in clean energy, of which 50% focused on research and development (R&D) for renewable energy. The investment in clean energy is expected to increase substantially to RMB 5.4 trillion (almost $800 billion) from 2009 through 2020. Given the sheer scale of China's market, its push to expand the role of clean energy technology is poised to play a key role in accelerating global clean energy innovation, which will benefit the world. Fig. 1 shows China's share of cumulative global additions to 2035 for selected clean energy technologies.

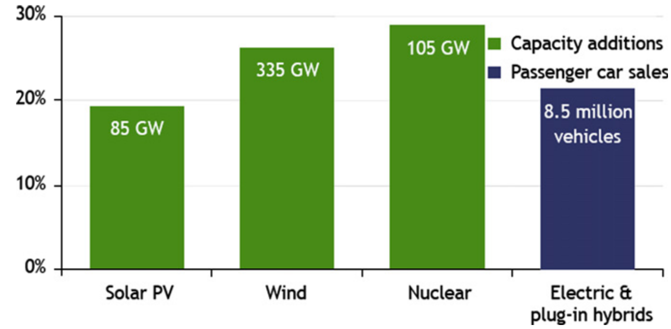

Fig. 1. China's share of cumulative global additions to 2035 for selected clean energy technologies [10].

Although its policies are far from perfect, there is much to be learned from China. This paper aims to provide a clear review of clean energy innovation in China, in order to accelerate global clean energy innovation. It's worthy of note that the paper cannot comprehensively address all components of the clean energy innovation in China. It aims to show the ways in which the Chinese government's science and technology (S&T) innovation goals and understanding about the changing dynamics of innovation are shaping its clean energy innovation policy orientation. It is formatted as follows. Section 2 analyzes the technology innovation process and major players. Section 3 decodes the Chinese way of innovation. Section 4 explores the clean energy technology innovation with Chinese characteristics. Section 5 analyzes lessons from China in clean energy innovation. Section 6 draws conclusions.

2. Understanding technology innovation

2.1. The innovation process

Technology innovation is a gradual process and evolves through different stages [12]. A number of stylized models of the technology innovation process have been proposed and refined during the last century [13]. Initially, these models conceived of innovation as a one-dimensional, linear, and sequential process beginning with R&D, then to demonstration, and finally to deployment (also called diffusion) in the marketplace (Fig. 2). Later, this theoretical model was refined to capture two-way or iterative "chain-linked" interactions whereby learning in one phase was linked to the other phases [14]. As currently understood, then, technology innovation

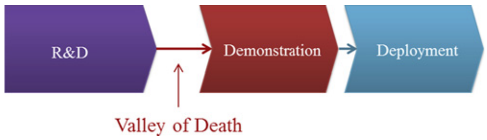

Fig. 2. Technology innovation process.

is characterized by multiple dynamic feedbacks between different stages of the process [15]. The linear model of innovation still widely used, though now being challenged as over-simplistic. It shares the same general schematic with the models stated above, without loss of generality.

R&D and learning are essential elements of the technology innovation process. No major changes can occur in existing technologies, unless explicit effort is made through research and development, however uncertain the outcome of such endeavors may be. But R&D spending that successfully leads to a new technological concept without the acquisition of experience through deployment that involves learning will make the technology that much harder to implement on a wide scale [16]. The "learning" can lead to cost reductions, greater proficiency in technology operation, as well as institutional transformations necessary to support the introduction and diffusion of new technologies and allow them to enter the realm of widespread use. Three ways by which leaning occurs have been identified as learning-by-doing, learning-by-using, and learning-by-interacting [17,18].

In competitive markets, firms tend to under-investment in R&D relative to the optimal level for society, for fear of being unable to capture adequate returns to justify the upfront investment. Generally, government has a pivotal role to play in correcting this market failure by offering some types of reward to encourage innovation. In this regard, "technology-push" and "market-pull" approaches are commonly used to promote technology innovation [19–22]. The "technology-push" approach aims to implement measures that can reduce the private cost of producing innovation, such as government sponsored R&D, tax credits for companies to invest in R&D, enhancing the capacity for knowledge exchange, support for education and training, and funding demonstration projects. The "market-pull" approach is developed to increase the private payoff to successful innovation through measures of intellectual property protection, tax credits and rebates for consumers of new technologies, government procurement, technology mandates, regulatory standards, and taxes on competing technologies.

2.2. A valley of death in the innovation process

Despite widespread acceptance that innovation is a process, the theoretical and practical consequences of making investments in a multi-stage framework are typically ignored [23]. In some cases, R&D is treated as synonymous with innovation. In others, particular stages are evaluated entirely separate from the others, ignoring the linkages between stages. Technologies in the early stages of the innovation process typically have significantly higher unit costs than the established alternatives. It is generally the case that the relative role of government in the funding and conduct of technology innovation shrinks and that of the private sector grows as one moves along the innovation process. The difficulty arises in the transition from R&D to demonstration, often referred to as the "valley of death", where public financing usually is dropping off and private financing has not picked up rapidly enough to invest in the pioneer technologies that have high economic and technical uncertainty without sufficient policy incentives [10,24,25]. For example, CO_2 capture and storage (CCS) represents an additional cost for industrial operators, and the first-of-a-kind demonstration projects are also likely to be the most risky and expensive CCS projects. Therefore, no one wants to be the first.

2.3. Major players and the role of government

The author has identified five major players whose participation is essential for technology innovation [10,26]. All five of these must work together for innovation to succeed because they are interdependent. No one of these players can innovate without the rest.

Researchers: The research, development, and even demonstration will be undertaken by researchers. The involvement of researchers contributes not only through the technological and scientific assets they bring, but also through the training and educating of the workforce needed for commercializing the technologies.

Consumers: As technology enter the marketplace, experiences from consumers using the technology in a niche market result in feedback loops to improve the innovation process. This usually occurs through learning-by-using, learning-by-doing, and economies of scale.

Investors: The share of government involvement generally decreases as technologies move closer to commercialization, and commercial deployment has traditionally been the responsibility of the private sector. Investors can play an important role in all the stages of the innovation process, which is capital intensive and relatively risky.

Entrepreneurs: An entrepreneur is an owner or manager of a business enterprise who makes money through risk and initiative. Being a risk taker is a natural trait of entrepreneurs. This ensures there is a reasonable chance of succeeding in driving the technology innovation process.

Government: Although there is a consensus that government intervention is critical to support basic R&D, there remains considerable controversy over whether and how government should be involved in all the stages of the innovation process, particularly in bridging the "valley of death". One reasonable argument is that the "valley of death" is an inherent risk associated with technology innovation process, so it would ideally overcome by competing for high-risk-taking venture capital. Another stronger argument is that the public-good nature of technology requires that government should play multiple roles in the innovation process, not only as major funders of research, development, and demonstration (supply-push), but also supporting the creation of a market environment that is more conducive to innovation, and stimulating market demand for technologies (demand-pull).

2.4. Challenges for innovation

Although many of the challenges for innovation are common to all countries, they are especially acute for many developing countries [5,6,10,27].

- Vision, strategy, and policy framework.
  Establishing a vision for what the government aims to achieve is a crucial first step. Governments must set ambitious technological challenges to inspire the private sector to pursue innovation. A shared vision provides the basis for a fruitful publicprivate dialogue on priorities and opportunities, and prevents governments from crowding out private investment. Achieving a vision requires a comprehensive strategy that integrates a portfolio of

policy tools adapted to both national systems and individual technologies.

- Intellectual property rights (IPR) protection.
  The institutional and policy challenges related to IPR protection include formulating appropriate policy and legislation, administering IPRs in line with international obligations, and enforcing and regulating IPRs in a pro-competitive manner appropriate to national levels of development. Developing countries will want to ensure that their IP regimes complement and enhance their broader policies for encouraging technological development and innovation.
- Infrastructure constrains.
  Infrastructure is essential for technologies in early stage of commercialization. Infrastructure projects are also often capital-intensive. There is a large gap between infrastructure needs and available capital and capabilities in developing countries, and developed countries, especially in an economic downturn.
- Human and institutional capacity.
  Human and institutional capital is an essential building block for innovation. Development of human skills in research, as well as strengthening those institutions that focus on educating the next generation of researchers, policymakers, entrepreneurs, and professionals, are particularly critical capacities for promoting innovation.

Given all the challenges mentioned above, developing countries are generally not in a strong position to assume the additional risks associated with technology innovation.

3. The Chinese way of innovation

3.1. Innovation as a national strategy

China has long used the slogan "Science and technology constitute a primary productive force" to promote innovation. However, the *National Medium-and Long-term Plan for S&T Development (2006–2020) – the MLP, for short* – released in 2006 elevated the priority of innovation to a national strategic level equal to Deng Xiaoping's "Reform and Opening-up" policy [28]. For the first time, China publicly declared that it aims to build itself into an innovative country by 2020, when scientific progress will contribute to nearly 60% of the nation's economic growth, and R&D investment will be more than 2.5% of its GDP (1.3% in 2006). The MLP has drawn the blueprint for future S&T innovation in China with an emphasis on creating a favorable policy environment for innovation.

The MLP establishes an innovation strategy for the S&T undertakings before 2020 consisting of four guiding principles: (1) Indigenous innovation. It refers to enhancing original innovation, integrated innovation, and re-innovation based on assimilation and absorption of imported technologies. This principle codifies the determination to reduce China's dependence on foreign technology and clarifies the central role of indigenous innovation in the whole national innovation strategy. (2) Leapfrogging in priority fields. It is to select and concentrate efforts in those key areas of relative strength and advantage linked to the national economy and people's livelihood as well as national security, to strive for breakthroughs and realize leaping developments. (3) Enabling development. It is an attempt to strive for breakthroughs in key, enabling technologies that are urgently needed for the sustainable and coordinated economic and social development. (4) Leading the future. It reflects a vision in deploying for frontier technologies and basic research, which will, in turn, create new market demands and new industries expected to lead the future economic growth and social development.

Based on the principles, this MLP identifies 11 priority areas for economic and social development, from which 68 priority topics of clearly defined missions and possible technical breakthrough in near term are selected. In line with national objectives, the MLP makes the arrangement for total of 16 special major projects, which hold the potential for providing leapfrogging development or fill up a blank. Looking strategically, the MLP identifies 27 frontier technologies in 8 technological fields, 18 basic scientific issues, and four major scientific research programs. In order to provide reliable support for China to become an innovation-oriented society, the MLP claims to deepen the S&T system reform, increase S&T investment, strengthen talent development, and promote the creation of a national innovation system.

Viewing science and technology as the key to economic development and international competitiveness, China's leading officials are deeply committed to research and development and have provided sustained attention and funding to realize their goals. In 2011, China reported to have spent 133 billion U.S. dollar on R&D, or 1.83% of its GDP [29]. The rapid rise in R&D expenditure in recent years is shown in Fig. 3.

3.2. Science, technology, and innovation governance

The Chinese science and technology system is pluralistic. There are many sources of support, many types of performers, and a maze of linkages amongst funders, performers, and users of science and technology.

As shown in Fig. 4, the State Council is the top administrative authority in China. Immediately below it are several ministries involved with various aspects of science and technology. The State Council S&T and Education Leading Group, currently chaired by Chinese premier Wen Jiabao and comprised of the leaders of the major science agencies, is established to review and authorize S&T development strategy and coordinate among different agencies. The Ministry of Science and Technology (MOST) plays a leading role in developing national science and technology strategy and policy and in designing and implementing many of the national research programs. The Ministry of Education (MOE) oversees education as well as research institutes at universities. The Ministry of Finance (MOF) provides financial support for science and technology development. The National Development and Reform Commission (NDRC), ministry-level chief economic planning agency, has policy, regulatory and administrative functions as well as the authority to approve technology demonstration and develop regulations and policies. Chinese Academy of

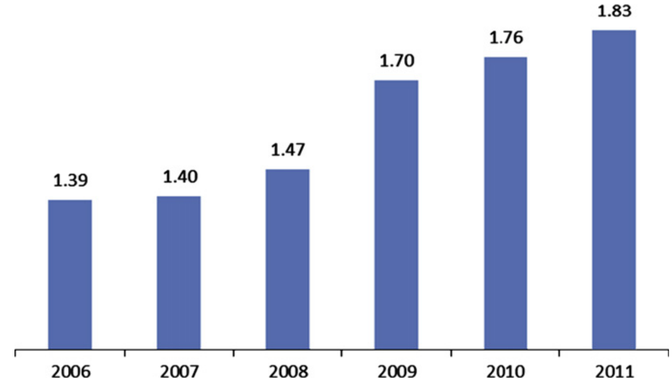

Fig. 3. National R&D expenditure (% of GDP) in China [29,30].

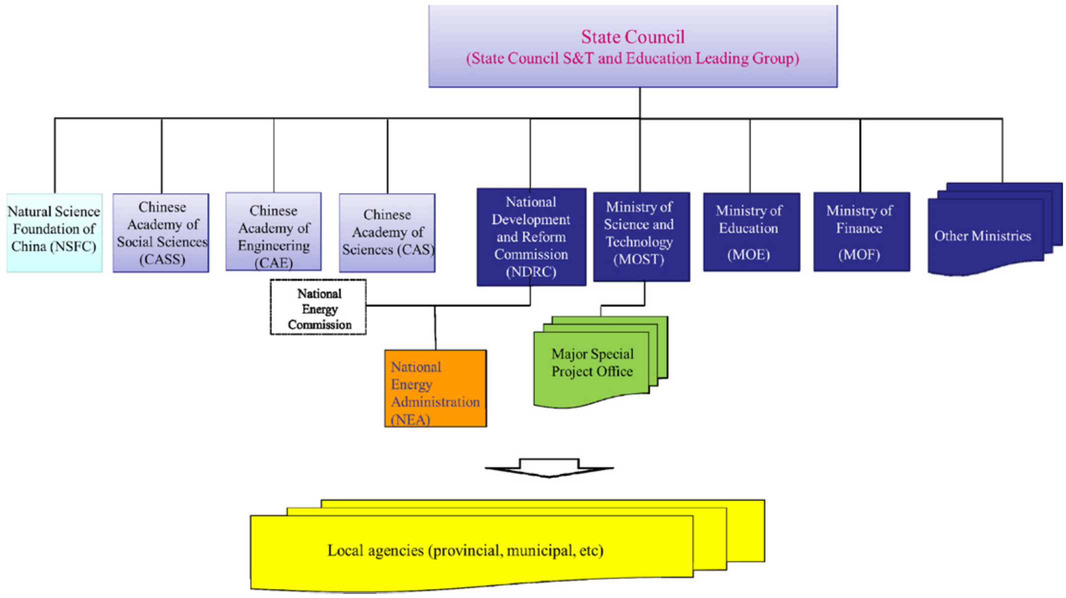

Fig. 4. Simplified governance structure of science, technology, and innovation in China.

Social Sciences (CASS) and Chinese Academy of Engineering (CAE) provide policy and strategy advises.

In China, there is no a unified department – like the U.S. Department of Energy – responsible for energy issues. Responsibility for making and implementing energy policy in China is shared among a number of different bodies at national and local levels. The National Energy Administration (NEA, vice ministry level agency) is under the supervision of the NDRC. The NEA takes the lead in the integrated administration of energy industry in concert with NDRC. To strengthen the coordination in formulating energy strategy and development planning, the National Energy Commission (NEC), headed by premier Wen Jiabao, was established to formulate energy strategy, review key issues on energy security and energy development, and coordinate among ministries and other government agencies. The general office of NEC is located in the NEA.

Chinese government expenditures for science and technology are included in annual budgets which are guided by priorities set in the MLP and the five-year economic plans. National programs are multiyear activities which are funded on an annual basis. The R&D budget is allocated first by Ministry of Finance to MOST, NDRC, Chinese Academy of Sciences (CAS), and Natural Science Foundation of China (NSFC). The funds will then be awarded to universities, research institutes, and enterprises. MOST allocates the R&D fund mainly through its national S&T programs, such as National Basic Research Program (“973” Program), National Key Technology R&D Program, National High-tech R&D Program (“863” Program); NDRC mainly support technology demonstration and diffusion. NSFC is an important source of funding for pre-commercial research at universities and CAS. NSFC grants are typically smaller grants than those provided by other major R&D programs, often in the hundreds of thousands of yuan, rather than the tens and even hundreds of millions of yuan for single projects seen in the grants from “863” and “973” Programs sponsored by the MOST. While NSFC continues to be an important source of basic research funding, its mission has expanded to support application-oriented research under its “key” and “major” programs. The CAS, which operates 100 research institutes in China, mainly performs basic and applied research through its “Knowledge Innovation Program” and a follow-on “Innovation 2020 Program”, which are outside the direct control of MOST [31]. As China’s leading S&T ministry, MOST are believed to constitute a small proportion (approximately 16% in 2009) of the national government’s expenditures on R&D. Local governments (provincial and municipal) have become far more important in supporting R&D and are now spending about half (around 49% in 2009) of all reported government spending on S&T and are working with national research organizations to establish new facilities for research and innovation within their jurisdictions [30]. At any one time, the funding programs will be supporting research in higher education institutions (HEIs), R&D institutes (RDIs), and enterprises. Funds are allocated through a competitive proposal process to projects that address innovation goals as determined by the MLP. Individual scientists seek funds from a variety of national programs, and it is often the case that important scientific efforts will be funded partially by various funding programs.

3.3. China’s quest for indigenous innovation

Since the start of the “Reform and Opening-up”, China has acquired vast amounts of know-how through technology transfer. Within around 30 years, China has emerged from a pure technology importer to a major manufacturer of advanced technology. Nevertheless, China is not yet an economic power primarily because of its weak innovative capacity. China has long been considered as “The World’s Factory”. However, Chinese enterprises are primarily engaged in low added-value, labor-, resource-, capital- and carbon-intensive manufacturing, with the more advanced aspects of product research, design, and development often being controlled by foreign entities [32,33]. As China’s economic reform progressed, many Chinese question whether China has become overly dependent on foreign technology in ways that are detrimental to its economy and national security [34]. Some Chinese argue the country should strive to develop its own technologies in order to capture new markets; others believe that the cutting-edge technologies China really needs are those that other countries are not willing to sell. To change the situation, Chinese government put forward “indigenous innovation” as a national strategy for the purpose of promoting the development of technology innovation in domestic firms, eventually leading to the ownership of their own core IPRs. The MLP highlights that the key to increasing indigenous innovation capacity is to strengthen the leading role of enterprises in

technology innovation to build up a technological innovation system that is led by enterprises, guided by the market, and characterized by collaboration of industries, universities, and research institutes.

3.3.1. Legislation, policy and institutional arrangements

The initiation of the MLP has been followed by the introduction of a large number of coordinated policy, legislation, and institutional arrangements.

Legislation: The domestic legal framework for protecting intellectual property in China is built on three national laws: the Patent Law, the Trademark Law, and the Copyright Law. As a member of World Trade Organization (WTO), China also committed to complying with the requirements of the WTO Trade-Related Aspects of Intellectual Property Rights (TRIPS) Agreement. This leads to the creation of a comprehensive legal framework to protect both local and foreign intellectual property in China. In 2008, China revised its Patent Law for the third time to amend those provisions that fit awkwardly with the indigenous innovation strategy as well as to make a transition to a national IP regime that is more in harmony with international norms [35].

Government procurement: Since 2007, China has introduced a series of policies to promote indigenous innovation through government procurement, mainly including a national-level catalogue of indigenous innovation products that will receive preferential treatment in government procurement. The policies provoked intense criticism from foreign firms on grounds that they discriminated unfairly against foreign firms. Given the controversy over the policies, Chinese government formally ended three of the government procurement rules linking to indigenous innovation in 2011 [36]. Nevertheless, there is no doubt that government procurement is an import instrument for promoting innovation. The best solution would be China's accession to the Government Procurement Agreement (GPA) under the framework of the WTO (China has agreed to join the GPA since it became a member of the WTO and began negotiations in 2007).

Institutional establishment: In 2007, the Major Special Project Office (MSPO) was established in the MOST to make the 16 major special projects proposed in the MLP happen. The MSPO was also established at provincial and municipal levels. In conjunction with the MOF and the NDRC, the MOST is responsible for project evaluation, coordination, and supporting policy implementation.

3.3.2. The strategy of "market for technology"

Besides domestic R&D investment, China's most notable way is through technology import. China's advancement in technology since 1949 has relied heavily on the import of foreign technology, with the strategy of "Money for Technology". Starting in the late 1970s, China introduced the "Reform and Opening-up" policy and pursued an active strategy of "Market for Technology", characterized by advanced technology acquisition, assimilation, and secondary innovation. Since then, Chinese enterprises have been shifting their spending from technology import to in-house R&D, which aims to promote secondary innovation through assimilation of the imported technologies (Fig. 5).

3.3.3. R&D, talent, and award programs

The Chinese government has placed emphasis through funding, talent recruitment, and award on science and technology as a fundamental part of innovation. Details are as below.

3.3.3.1. National research programs. The MOST runs three major funding programs to spur technology innovation in China [37]:

National Basic Research Program ("973" Program): This is a program for "the day after tomorrow". In line with national strategic needs, this Program aims to conduct basic, forward-looking, far-reaching as well as strategic research that may trigger remarkable changes in economic and social sectors. It also reinforces comprehensive cross-disciplinary research and innovative integration to develop new ideas, concepts, inventions, and theories so as to lay a solid foundation for leapfrog development.

National High-tech R&D Program ("863" Program): This is a program for "tomorrow". Focusing on the R&D of cutting-edge technologies, the Program aims to boost innovation capacity in vital areas where China has relative strength and advantage linked to the national economy and people's livelihood as well as national security.

National Key Technology R&D Program: This is a program for "today".Combining the R&D of strategic and generic technologies with national major construction projects or major equipment development projects, the Program strives for breakthroughs that are urgently needed for the sustainable and coordinated economic and social development.

While these three programs consume only a small portion (9.4% in 2009) of the government's annual R&D expenditures, they are large in their impact on frontier technologies that China has developed in areas crucial to its global competitiveness. In recent years, the central government has increased funding for these programs than at any other time in their history, as shown in Fig. 6 below.

These Programs cover all major elements of technology innovation, ranging from R&D, demonstration, and commercialization. All of these Programs – literally "plans" in Chinese – are characterized by the strong legacy of the planned economy: These Programs are designed and implemented through a top-down "picking-the-winner" approach, with a limited involvement of

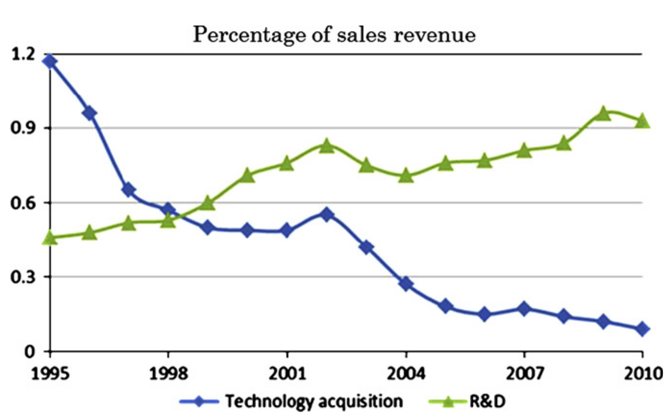

Fig. 5. Expenditures on R&D and technology acquisition by Chinese large and medium-size enterprises (LMEs), 1995–2010 [30].

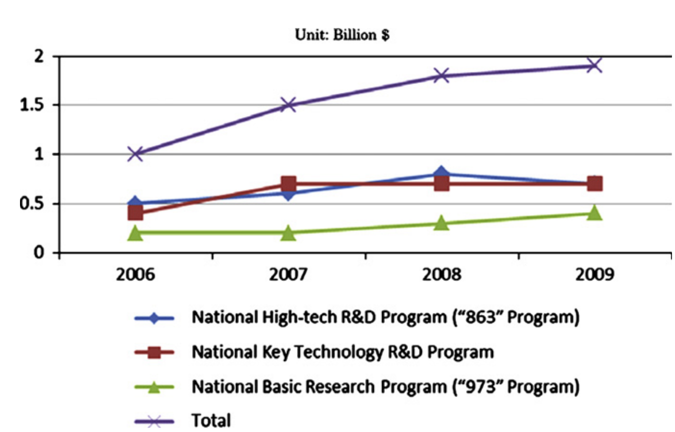

Fig. 6. R&D expenditures on the three major national research programs [30,38].

key stakeholders from non-government sector, especially the private sector. Chinese scientists have called into question the effectiveness of the funding mechanism and the overall S&T system [39]. Government agencies are seen as executing technology development plans with little coordination across the government. Various entities – and even national program offices within MOST – have overlapping goals and pursue their missions in a stovepiped fashion that leads to waste and duplication of efforts [40]. There is also a large potential in improving program evaluation. The interference from government officials and university bureaucrats makes peer review far less effective in China than it could be.

3.3.3.2. National talent programs. **The Recruitment Program of Global Experts (Thousand-Talent Program):** The Program is initiated in 2008 by the Organization Department of the Central Committee of the Communist Party of China (CPC). It has now become an international headhunter and the highest and most esteemed national talent program, with the goal of attracting some 2000 top scientists and talents to work in China over the next five to ten years [41].

The Changjiang Scholars Program: The Program, jointly established by the Chinese Ministry of Education and the Li Ka-Shing Foundation, is the highest form of recognition from the Ministry. It was started in August 1998, and provides scholarship funding to allow well-known professors from China and other countries to work in China [42].

3.3.3.3. National science and technology awards. To recognize those who have made remarkable contributions to scientific and technological progress, Chinese government established five national awards, covering science and technology, natural sciences, technical invention, scientific and technological progress, international cooperation in science and technology [43]. These awards are presented by the President of China at the annual National Science and Technology Awards Ceremony.

The National Supreme Science and Technology Award is China's highest and most esteemed national honor in science and technology. The award is handed out each year to no more than two scientists. Winners receive a cash prize of 5 million yuan. It honors scientific and technological breakthroughs, with far-reaching influence. It also rewards prominent scientists who have generated enormous economic returns or facilitated social progress in technology innovation and commercialization. The National Natural Science Award honors achievements in basic and applied research. The National Technology Invention Award honors important technology inventions. The National Science and Technology Advancement Award honors advanced technology commercialization and deployment. The International Science and Technology Cooperation Award honors foreigners or international organizations that have contributed to the advancement of China's science and technology development.

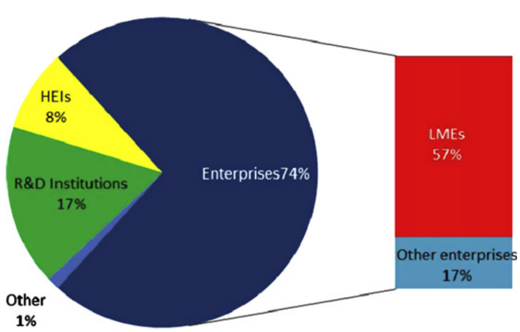

Fig. 7. R&D expenditure by performer, 2010 (total: $ 103 billion [30]).

3.3.4. Major national science and technology innovation performers

China's market-oriented reforms and the opening up of its economy have moved it away from the government-led model of technological innovation toward one that is enterprise led and market based. Over the past decade or so, business enterprises have replaced RDIs and HEIs, which are largely government owned, to become the largest sector for R&D. As shown in Fig. 7, in 2010, RDIs and HEIs jointly accounted for 25% of China's total R&D expenditure. In contrast, 74% of total R&D expenditure was spent by enterprises—of which 57% was shared by large and medium-size enterprises (LMEs) [30]. While business enterprises overall have replaced RDIs and HEIs to become the most important performing sector of R&D in China, the role of small enterprises remains limited. Thus, it is LMEs owned and controlled by the state that now conduct the largest portion of R&D in China. It' worthy of note that despite the growth of research in Chinese enterprises, the role of the government remains central to China's innovation system, with national funding programs supporting most of the nation's advanced R&D programs.

Much more attention is being given today to university-industry-research partnership in the belief that universities and public research laboratories should mainly conduct basic scientific and pre-commercial research, while industrial firms perform

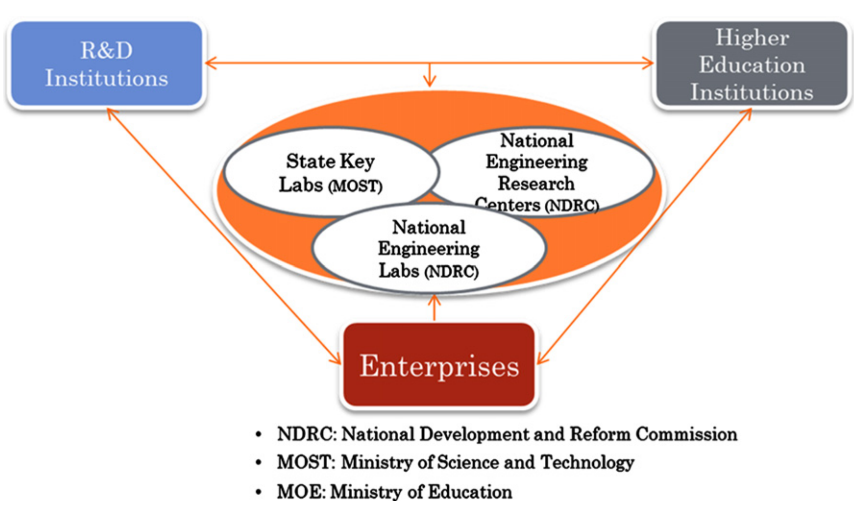

Fig. 8. Major national science and technology innovation performers in China.

the bulk of the applied research and development that is necessary before introducing new products and processes to the marketplace. Fig. 8 shows the major technology innovation performers of RDIs, HEIs, and enterprises. Among these, more than 300 State Key Labs sponsored by MOST for basic and applied research and 86 National Engineering Research Centers and 85 National Engineering Labs located in HEIs, RDIs, and enterprises and granted by NDRC for technology demonstration and diffusion, take the leading role in S&T innovation [38].

4. Clean energy technology innovation with Chinese characteristics

4.1. A strong legacy of a centrally planned economy

A defining characteristic of the Chinese innovation model is its tradition of centrally-planned initiatives and the national mobilization of all the necessary resources needed to support their implementation. These efforts produce a model of top-down, state directed S&T programs to spur innovation in strategically important areas. China's FYP for National Economic and Social Development is one of primary tools used by the government to achieve its overall development objectives by mapping out in five-year cycles the nation's future progress via guidelines, policy frameworks, and targets for policy-makers at all levels of government.

The FYP relies on key indicators to help achieve broader principles. Key indicators related to clean energy innovation are described as below [44,45]:

- **R&D expenditure**: The policy of indigenous innovation will continue to play a central role throughout the 12th FYP period. A key priority of the 12th FYP is for China to transition from "Made in China" to "Designed in China." In order to achieve this goal, China aims to put 2.2% of its GDP into R&D by 2015. R&D as a percentage of GDP was one of three nonrestrictive indicators that China failed to meet in the 11th FYP: R&D in China accounted for 1.75% of GDP in 2010, far below the government's expected goal of 2% for 2010.
- **Energy intensity and carbon intensity of energy use**: China aims to cut the amount of energy consumption and CO_2 emissions needed for every unit of GDP by 16% and 17%, respectively, over the five years to 2015. This is consistent with China's long-term plan to cut carbon intensity by 40% to 45% by 2020, relative to 2005 levels.
- **Non-fossil energy**: The 12th FYP aims to increase the share of non-fossil fuel in the primary energy consumption from 8.7% in 2010 to around 11.4% by 2015, aligning with China's pledge to have 15% of its energy come from non-fossil fuels by 2020. The 12th FYP also calls for a 250 gigawatt (GW) increase in hydropower capacity, a 90 GW increase in large offshore wind power capacity, a 40 GW increase in nuclear power capacity, and a 5 GW increase in solar energy installed capacity, though Japan's recent nuclear crisis has led to a temporary suspension of new construction.
- **Cap on energy consumption**: The FYP includes a cap on total primary energy consumption at approximately 4.1 billion tons of coal equivalent by 2015. The breakdown under discussion would include around 3.8 billion tons of coal.
- **Investment on Strategic Emerging Industries (SEIs):** Chinese planners have included several preferential tax, fiscal and procurement policies designed to develop seven "Strategic Emerging Industries" (SEIs): biotechnology, new energy, high-end equipment manufacturing, energy conservation and environmental protection, clean-energy vehicles, new materials, and next-generation IT. The government is reportedly prepared to spend more than RMB 4 trillion on these industries during the 12th FYP period, with an aim to increase SEI's contribution from today's approximately 3% of GDP to 8% by 2015 and 15% by 2020.

4.2. Indigenous innovation through re-innovation

The MLP defines indigenous innovation as original innovation, integrated innovation, and re-innovation based on assimilation of imported technology. As illustrated in Fig. 9, China has been seeking two approaches to innovative clean energy technologies. One is through government-led R&D to make original innovation; another is through the decoding of clean energy technologies imported from the developed countries to make secondary innovation.

Obviously, technology transfer is a crucial part of the process of clean energy innovation in China. China has been importing advanced clean energy technologies through various approaches [23,46]:

1. **Joint venture:** Joint venture is contractual arrangement between two (or more) firms in which each provides some advantage that should make the joint operation successful. For example, the foreign participant will make the advanced technology available while the domestic firm provides its knowledge of the local market, the domestic regulatory and business environment, and some other local advantages. Joint venture mechanism can help foreign firms easily access to the Chinese market and freely use their own business model. The transfer of technology through this arrangement nevertheless has certain limitations. For instance, such technology

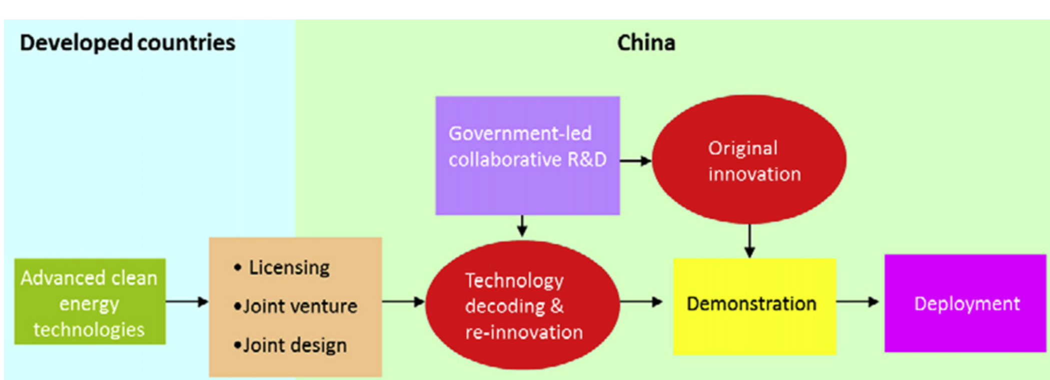

Fig. 9. Clean-energy-technology-innovation pipeline in China.

transfer may unwillingly result in a loss of competitiveness and market share in the mid to long term, considering foreign partners might then become competitors within and outside China. Therefore, foreign firms are very reluctant to share ownership of advanced technologies with local partners. Because of this drawback, many joint ventures in China act as manufacturers or post-sale maintenance facilities instead of technology developers.

2. **Licensing:** Licensing involves the purchase of production rights, protected by IPRs, and in many cases, the provision of technical assistance and know-how, which are needed to adopt and adapt the technology. The transfer of tacit knowledge and the provision of technical services are central to ensure that the licensor will secure the proper capabilities so as to use the technology in an effective way. However, the tacit knowledge is complex and therefore difficult to define in the contractual arrangement.
3. **Joint design:** Through joint design, the phases of absorption, adaptation, and assimilation of subsequent improvements are in a sense embedded in the collaboration process, which is likely to reduce the total life cycle cost required to get the job done.

To localize core energy technologies, the Chinese government made a comprehensive plan for each identified technology. At the early stage of localization, the "973", "863", and National Key Technology R&D Programs are the main instruments to support decoding efforts. Once a technology has been decoded, a set of incentive policies and regulatory mandates are introduced to scale-up commercialization and drive down costs of the technologies.

It is true that some Chinese enterprises are increasingly innovative, that a small number of them are even approaching the international technological frontier, and that the general level of technological progress of Chinese industry has been rising over the past three decades [48]. Nonetheless, the overall picture remains that the global competitiveness of China's leading manufacturing sectors rests upon low input costs, scale of production, technology absorption, speed of response to market demands and customer orders, and increasing attention to the quality of products [32]. Most leading Chinese enterprises remain manufacturers and assemblers of products without possessing core technologies. For example, China now is the largest thermal power equipment manufacturer in the world. Shanghai Electric, Harbin Electric, and Dongfang Electric have emerged as three major manufacturers in China. Their annual outputs all exceeded 35 GW in 2007, higher than any other major manufacturer around the world. In addition to supplying the domestic market, China has increased supercritical (SC) and ultra-supercritical (USC) equipment exports to other developing countries. To manufacture state-of-the-art products, China acquires the designs for turbines, boilers, and generators from industry leaders in developed countries through joint ventures or by purchasing licenses (Table 1). However, such firms typically do not transfer all parts of a technology to China, holding back some of their IPR [46]. For instance, in addition to sourcing some core technology designs internationally, China still largely depends on imports to obtain alloys that can sustain high pressure and high temperature for the USC boiler. In addition, China's third-generation pressurized water reactors are the first in the world to use advanced passive 1000 (AP1000) technology developed by Westinghouse. Based on the technology, China will develop a variation of the AP1000 technologies, trumpeted as the "home-grown" CAP1000, as well as an updated CAP1400.

4.3. The role of a global learning laboratory

As previously stated, China has been relying heavily on transfer of advanced technologies for re-innovating clean energy technologies. China is, therefore, not a powerful country in discovering fundamental knowledge, which is source of scientific applications. China's strength in clean energy innovation lies on its vibrant market. This is commonly known as "big D (development) and small R (research)." China is demonstrating some clean energy technologies that have never been used in other countries due to higher cost, technological uncertainty, strict regulations, and relatively limited market. For instance, The technology transfer between Westinghouse Electric Company and China's State Nuclear Power Technology Corporation (SNPTC) will definitely open up unique transnational learning opportunities between the United States and China where the lessons learned building the first AP1000 plants in China will be shared with the two U.S. utilities now embarking on new plant construction in Georgia and South Carolina, respectively.

Thanks to its relatively loose regulations, cheap labor, and huge market for clean energy technologies, China has become a global learning laboratory of clean energy. Table 2 shows the clean energy technologies that was, is or will be demonstrated during the 11th (2006–2010) and 12th FYP (2011–2015).

Table 1
Sources of 1000 MW level USC and AP 1000 and transfer mechanisms in China [46,49,50].

Technology	Company	Product	Technology source	Transfer mechanism
1000 MW USC	Shanghai Electric	Boiler	Alstom	Licensing
		Turbine	Siemens	Joint venture
		Generator	Siemens	Joint venture
	Dongfang Electric	Boiler	Hitachi	Licensing
		Turbine	Hitachi	Licensing
		Generator	Hitachi	Licensing
	Harbin Electric	Boiler	Mitsubishi	Licensing
		Turbine	Mitsubishi	Licensing
		Generator	Mitsubishi	Licensing
AP 1000	State Nuclear Power Technology Corporation (SNPTC)	Nuclear island design	* Westinghouse * Shaw	
		Equipment design and manufacturing	* SPX	
		Nuclear zirconium manufacturing	* Curtiss-Wright	
		Instrument control design and supply	* Ansaldo Nucleare	Licensing
		Fuel design and manufacturing	* DOOSAN	
		Engineering project management and operation and maintenance	* Licensing	

Table 2
Advanced clean energy technologies in China during 2006–2015 [51–56].

Category	Technology	Development status
Clean coal power	USC Integrated gasification combined cycle (IGCC) Large circulating fluidized bed (LCFB)	⁎ The first 700 °C Advanced USC (A-USC) will be demonstrated during the 12th FYP. ⁎ The first 1000 MW USC started to operate during the 11th FYP. ⁎ The first 400–500 MW level IGCC co-production will be demonstrated during the 12th FYP. ⁎ The first 250 MW IGCC is undergoing testing for possible commissioning. ⁎ The first 600 MWe Supercritical CFB has been demonstrated during the 11th FYP.
Coal to liquids (CTL)	Direct conversion Indirect conversion	⁎ The first demonstration project (1 Mt petroleum products) began operation during the 11th FYP. ⁎ The first demonstration project (0.16 Mt petroleum products) began operation during the 11th FYP.
Coal to natural gas	Gasification-based Hydromethanation-based	⁎ The first project (1.35 billion cubic meters) will be demonstrated during the 12th FYP. ⁎ The first project (0.85 billion cubic meters) will be demonstrated during the 12th FYP.
CCS	Post-combustion capture Pre-combustion capture CO_2 storage by saline aquifer CO_2-enhanced oil recovery (EOR) CO_2-enhanced coal bed methane (ECBM)	⁎ The first integrated CCS for EOR project (0.5–1 Mt CO_2/year) will be demonstrated during the 12th FYP. ⁎ Three projects of 3000 t/year, 10 kt/year, and 120 kt/year CO_2 captured have been demonstrated during the 11th FYP. ⁎ The first demonstration in GreenGen project will be demonstrated during the 12th FYP. ⁎ The first 100 kt/year integrated CCS (CO_2 from the CTL project) was constructed during the 11th FYP, and was put in operation during the 12th FYP. ⁎ The first 100 kt/year oil project was demonstrated in Jilin oil field during the 11th FYP. ⁎ The first project was demonstrated in Qinshui basin during the 11th FYP.
Nuclear power	High Temperature Reactor (HTR) AP1000 Fast reactor Small modular reactor (SMR)	⁎ The first 200 MW project will be demonstrated during the 12th FYP. ⁎ The first 1250 MW project will be demonstrated in Sanmen, Zhejiang province during the 12th FYP. ⁎ The first 20 MW China Experimental Fast Reactor (CEFR)was put in operation in 2011. ⁎ SMR will be demonstrated during the 12th FYP.
Solar power	Solar photovoltaics (PV) Concentrating Solar Power (CSP)	⁎ The first 100 MW level solar PV project will be demonstrated during the 12th FYP. ⁎ The first 10 MW solar PV project was demonstrated during the 11th FYP. ⁎ The first 300 MW level CSP coupled with coal power plant, 50 MW CSP (parabolic), 100 MW CSP (tower) projects will be demonstrated during the 12th FYP.
Wind power	Onshore/offshore	⁎ The first offshore wind farm with 6 MW wind turbines will be demonstrated during the 12th FYP. ⁎ 1.5–3 MW wind turbines have been commercialized during the 11th FYP.
Biomass	Power generation Biofuel	⁎ 25 MW and 50 MW biomass power generation and biomass–coal co-firing technologies have been commercialized during the 11th FYP. ⁎ Cellulosic to ethanol fuel technology will be demonstrated during the 12th FYP. ⁎ 200,000 t/year cassava to ethanol fuel project has been demonstrated during the 11th FYP. ⁎ The first-generation biofuel technology has been commercialized during the 11th FYP.
Clean energy vehicles	Electric vehicle (EV) Alternative-fuel vehicle Hybrid-electric vehicle (HEV)	⁎ Various EVs including fuel cell have been demonstrated in several cities during the 11th FYP. ⁎ Ethanol, methanol, Dimethyl ether (DME), LPG, CNG, LNG have been demonstrated at scale during the 11th FYP. ⁎ Various HEVs have been demonstrated during the 11th FYP.
Synthetic utilization of multiple energy resources	Wind–solar Hydro–solar	⁎ 100 MW wind–solar synthetic utilization project will be demonstrated during the 12th FYP. ⁎ 10 MW hydro–solar synthetic utilization project will be demonstrated during the 12th FYP
Power grid transmission and transformation	Transmission	⁎ $\pm$1000 kV direct-current (DC) long-distance transmission project will be demonstrated during the 12th FYP.
	Transformation	⁎ Large-scale intermittent power grid transmission and transformation project will be demonstrated during the 12th FYP.
Smart grid	/	⁎ Smart grid project will be demonstrated during the 12th FYP.

5. Lessons from China

5.1. A broader understanding of technology transfer

One of the most attractive notions in the field of sustainable energy development is the concept of energy-technology "leap-frogging". Leapfrogging through international technology transfer can be especially problematic because often China and other developing countries do not have the technological capabilities to produce or integrate the advanced energy technologies themselves. The lesson we learned is that TT is not just the transfer of hardware from developed countries to developing countries. It is also transfer of knowledge to improve China's indigenous innovation capacity [57–60].

5.2. A vicious circle among indigenous innovation, technology transfer, and regulation

Innovation presents risks as well as opportunities, and those risks can be reduced by IPR protection. Weak IPR creates uncertainty and disincentives for innovation. In the absence of adequate IPR, fewer people will accept the risks involved with innovation, and the rate and scope of innovation will slow.

There is a vicious circle among technology transfer, innovation, and regulation. For example, weak IPR protection can create adverse effects for both indigenous innovation and technology transfer. Thus, China will fall even further behind the developed countries in innovation capacity. Then the Chinese government is unlikely to take the risk to impose more stringent IPR protection and regulation, and the downward spiral continues.

There are two ways to break the vicious circle [47,61]. One is to improve and develop domestic technological capabilities for the clean energy technologies. This is exactly what the MOST is trying to do through its National Research Programs. The other way to break the vicious circle is for the Chinese government to gradually introduce the regulations and simply push the domestic firms to improve their capacities.

5.3. A balanced approach: indigenous innovation vs. technology transfer

The Chinese government has made it a top priority to enhance the country's indigenous innovation capability. However, innovation is a production and investment activity. China needs to consider the cost and risks during the process. Developed world has a more advanced S&T innovative system, a well-established regime for bringing technologies to market, and an abundant of capital and strong risk-taking capabilities, where they hold comparative advantages. For China, if it overly stresses on original innovation, it is very likely that the benefits brought about may be overshadowed by the cost paid by China.

A successful indigenous innovation policy will naturally lead to a decline in China's dependence on foreign technology [33]. However, achieving the right balance between indigenous innovation and technology transfer means that the optimal level of independence from foreign technology is not the highest one but the one that contributes most to the technology advancement and ultimately to the sustainability of economic growth. While it should take the private market to find out and approach such an optimal level in the long term, government has a key role to play in introducing a comprehensive efforts to improve the domestic absorptive capacity, which determines the speed with which they move on to indigenous innovation.

5.4. A sober understanding of the role of government in technology innovation

There is a common assertion that governments should avoid providing targeted support to particular technologies. Instead, they should set general frameworks to encourage more sustainable innovation. The practice of "picking winners or losers" should therefore be avoided because governments are not best placed to decide which technologies to fund [10,27]. However, the empirical foundations for such sweeping judgments remain remarkably fragile [62]. There are also reasonable arguments on a number of grounds [6,63,64]. First, the resources that governments can devote to clean energy innovation are limited, which is particularly true in developing countries. If there is no attempt to priorities how these limited resources are used, there is a risk that they will be spread too thinly. Second, the urgency of the twin challenges of energy security and environment protection we are facing today means that market mechanism alone would not be sufficient to develop those technologies that are not already close to commercial status. Third, private markets often under-investment in new technologies. Empirical evidence suggests that as a result of spillovers of all kinds, the social returns to R&D spending on new technologies far exceed the private returns, perhaps by as much as 50% to 100%. Private rates of return may not equal social rates of return—companies often cannot appropriate all the social benefits of an innovation and so fail to invest in what could be socially optimal technology.

The market can be a good thing and even necessary, but there is no evidence that private investment is any more capable than public investment of separating the winners from the losers before the fact. The evidence in China, as illustrated in this paper, is so overwhelming that the only conclusion that one can reach is that the argument against picking winners is especially wrong for emerging technologies that require deep and persistent public support. China's advance in clean energy technology is a result of long-term government research and development.

5.5. A reflection of the "state advances as the private sector retreats"

Although active government involvement in innovation is common in the successful catch-up economies in East Asia, none of the successes can be attributed to a reliance only on SOEs [33]. However, in recent years, China has adopted the statist approach to financial crisis starting from 2008, which has led to the dominance of China's state-owned enterprises (SOEs), at the expense of the private sector. The trend has given rise to a catch-phrase among Chinese: "Guo Jin, Min Tui," or "state advances as the private sector retreats".

Catch-up is not about advances in a few high-tech sectors. It means the upgrading of the economic infrastructure and innovation capacity of a nation's industry as a whole, which can be made possible only by the collective action of private enterprises that were highly motivated to push their technological frontier outward. From that perspective, it is of strategic importance for China to invest in technology capacity building of the emerging private sector.

6. Conclusions

China as developing country has been becoming a global leader in commercializing clean energy technologies, and it has become a global learning laboratory of clean energy technologies. China's leadership in commercializing clean energy technology could ultimately help lower its costs and promote its commercialization globally, representing a major step forward to promoting the global clean energy innovation system and solving the global climate dilemma.

Combined with its low-cost manufacturing, huge domestic market, and the role of a global learning laboratory, China's comprehensive efforts in advancing indigenous innovation have been proven remarkably effective in enabling China's technological catch-up and leadership in commercializing advanced clean energy technologies. However, the Chinese model of innovation currently characterized by import, assimilation, and re-innovation has not yet fostered the widespread commercialization of internationally-competitive technologies originating from Chinese R&D efforts.

In the past, China has devoted much of its best efforts to the absorption of the fundamental knowledge which has been discovered abroad—mainly in advanced economies. In the future, new impetus must be given to basic research since scientific

applications of the future will be more than ever dependent upon basic knowledge.

There is uncertainty about the future of China's clean energy innovation. Although the Chinese government has struggled to balance its need to utilize foreign sources of technology with a desire to nurture indigenous innovation, the path China navigates between planning and free market, and the twin-pronged and uncoordinated approach of buying advanced foreign technology while investing in indigenous innovation, will have profound implications for China's clean energy innovation.

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